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A Rule for Reducing Error Remains in Multicopy Transmission ARQ

사본 중복 전송 ARQ에서 잔류 오류의 감소를 위한 규칙

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Abstract

In ARQ based error control, imperfect error detection leaves error remains on a packet. Aiming for a reduction of error remains in multicopy transmission ARQ system, we propose a rule of requesting a retransmission and deciding a correct copy, (identified as (M, σ) rule). While the probability of error remains is reduced by the employment of the (M, σ) rule at multicopy transmission ARQ, delay and throughput performance may be degraded in comparison with those of conventional single copy transmission ARQ. Thus, we develop an analytical method to evaluate the performance trade-off in multicopy transmission ARQ following the (M, σ) rule. From the numerical results obtained by the analytical method, we investigate the effect of channel characteristics on the performance of error remains, packet loss, throughput, and packet delay, and confirm that the adaptability of the (M, σ) rule to conform to various QoS requirements with ease.

Keywords: ARQ, multicopy, error remains, delay, throughput, queueing

요 약

ARQ 기반의 오류 제어에서 불완전한 오류 검출로 인해 패킷에 오류가 잔류하게 된다. 본 논문에서는 사본 중복 전송 ARQ에서 잔류 오류를 감소시키기 위한 재전송 요청 및 오류없는 사본의 결정 규칙을 제안한다. 이러한 (M, σ) 규칙을 사본 중복 전송 ARQ에 적용할 때, 잔류 오류는 감소하나 기존의 단일 사본만을 전송하는 ARQ에 비해 지연 및 throughput 성능은 열화될 수 있다. 따라서 (M, σ) 규칙이 적용된 사본 중복 전송 ARQ에서 야기되는 성능의 trade-off를 평가하기 위한 해석적 방법을 개발한다. 이러한 해석적 방법으로 구한 계량적 결과로부터 (M, σ) 규칙의 파라미터, 채널의 성질, 트래픽 부하가 오류 잔류 확률, 패킷 상실, 패킷 지연, throughput 등에 미치는 영향을 검토하여 다양한 QoS 요구 조건을 용이하게 수용할 수 있는 (M, σ) 규칙의 적응성을 확인한다.

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Ⅰ. Introduction

Automatic repeat request (ARQ) is an error control scheme based on packet retransmission [1]. In ARQ schemes, the receiving node sends a retransmission request message if it detects errors in the received packet. Upon reception of a retransmission request message or negative acknowledgement (NACK) message for a packet, the transmitting node retransmits the packet. Thus, the transmitting node send a copy of a packet instead of the original, and remove the original after it receives a positive acknowledgement (PACK) message for the packet.

With an exaggeration of the property to send a copy of a packet, variants of ARQ were proposed to send multiple copies of a packet rather than a single copy [2][3][4]. Such multicopy transmission ARQ (MC−ARQ) was revealed to exhibit better throughput performance than a conventional ARQ scheme (of transmitting a single copy of a packet) when the propagation delay between transmitting and receiving nodes is significantly long compared with the packet transmission time or when the channel is extremely noisy.

In the receiving node, as mentioned above, an error detecting function should be performed to determine to send a retransmission request message or not. Since the error detection is imperfect, however, there may remain errors on a packet even after the receiving node sends a PACK message for the packet. The error remains may invoke an end−to−end retransmission which imposes a high cost in wireless networks supporting terminal mobility. In MC−ARQ, identical copies of a packet are spread in time domain. Thus, we can use a technique of time diversity combining to enhance the performance in probability of error remains.

In this paper, we consider MC−ARQ schemes and propose a rule of requesting packet retransmission and deciding a correct copy, identified as (M,σ) rule, to reduce the probability of error remains at the receiving node. In the (M,σ) rule, identical M copies of each packet are consecutively sent to the receiving node. Upon reception of the M copies, the receiving node inspects each copy for error. If no error is detected in more than or equal to σ copies, then a PACK message is sent to the transmitting node, and then a copy is chosen as a correct one by following majority decision rule. As increasing the values of M and σ, we are able to decrease the probability of error remains by use of time diversity combining. However, the packet transmission time increases as M increases and the number of retransmissions also increases as σ increases. As a result of such increase in packet transmission time and retransmission number, throughput and delay performance is degraded at networks in which the propagation delay between transmitting and receiving nodes is relatively low, (e.g., wireless cellular networks). For a quantitative evaluation of the performance trade−off incurred by the (M,σ) rule, we develop an analytical method to calculate the probability of error remains, packet loss probability, moments of packet delay time, and maximum throughput. Using the analytical method, we investigate the effect of channel's bit error rate and traffic load on the performance of error remains, packet loss, packet delay, and throughput.

In section 2, we describe the (M,σ) rule applied to MC−ARQ. In section 3, we introduce an analytical method to evaluate the performance of MC−ARQ following the (M,σ) rule. Section 4 is devoted to numerical examples demonstrating the effect of channel characteristics and traffic load on the performance of the (M,σ) rule.

Ⅱ. (M,σ) Rule for MC−ARQ

We consider stop−and−wait and go−back−N MC−ARQ schemes for node−to−node error control. The protocol data unit (PDU) defined in the layer performing error control is identified as a packet. The transmitting node makes M copies of each packet (to be transmitted) and sends them consecutively to the receiving node along the forward channel. Upon reception of the all M copies, the receiving node inspects each copy for error. A threshold value $\sigma \in \{1,\cdots,M\}$ is prescribed for the receiving node.

If no error is detected in more than or equal to σ copies among the M copies, then the receiving node sends a PACK message to the transmitting node across the reverse channel. Otherwise, a retransmission request message (or equivalently NACK message) is sent to the transmitting node. The retransmission of a packet is limited to $\nu \in \{0,1,\cdots\}$ times. Thus, if a retransmission request message (or NACK message) for a packet arrives at the transmitting node, the transmitting node counts how many times the copies of the packet have been already retransmitted. If the number of retransmissions reaches the limit number ν, then the transmitting node declares that the packet is lost. Otherwise, the transmitting node makes M copies of the packet again and retransmits them consecutively.

Once the receiving node sends a PACK message for a packet, it finds a correct copy among the copies in which no error is detected. For such decision, we use a majority decision rule as follow. If no error is detected in more than or equal to σ copies, the receiving node gathers the copies in which no error is detected. Due to imperfect error detection, such copies may still contain errors and thus may not be identical. If all the copies are not identical, the receiving node collects same copies and makes a group of them. After grouping all the copies in which no error is detected, the receiving node counts the number of copies belonging to each group and chooses the biggest group. Finally, the receiving node decides that the copies in the biggest group are correct. In case that there are two or more biggest groups, the receiving node selects one of them by use of a uniform randomizer. Note that such a decision rule to find a correct copy is equivalent to the maximum likelihood decision rule if the probability that errors occur in a copy is less than $1/2$.

Ⅲ. Performance Analysis of MC-ARQ following (M, σ) Rule

In this section, we present an analytical method to calculate probability of error remains, packet loss probability, moments of packet delay time, and maximum throughput when the (M, σ) rule is applied to stop-and-wait MC-ARQ and go-back-N MC-ARQ, respectively. A packet (the PDU defined in the layer performing node-to-node MC-ARQ) is of length N, which is constructed from K bit payload encoded by an (N, K) block code. In the transmitting node, M copies of each packet are transmitted with fixed data rate of ζ through the forward channel. The forward channel is slotted. Each transmission of a copy always starts at the beginning of a slot and the slot duration time is equal to the time to transmit a single copy. Such forward channel is modeled as a binary symmetric channel (BSC) characterized with bit error rate of α. Upon reception of M copies of a packet, the receiving node sends a PACK or NACK message along the reverse channel. We assume that the length of a PACK (NACK) message is negligible and that the reverse channel is a noiseless channel. The propagation delay time between transmitting and receiving nodes is fixed to ξ.

3.1 Probability of Error Remains

Suppose that packet copies of length N are sent through a BSC characterized by bit error rate α. Let ε be the probability that errors occur in a copy. Then, $\varepsilon=1-(1-\alpha)^N$. Let δ denote the probability that errors occur in a copy and such errors are not detected. In the (M, σ) rule, the receiving node receives M copies of a packet and inspects each copy for error. If the receiving node detects errors in more than $M-\sigma$ copies, then it sends a retransmission request (NACK message). Let U denote the number of copies in which no error is detected when the receiving node sends a PACK message, (i.e., the number of copies in which no error is detected is equal to or exceeds σ). Then, we have the mass for the random variable U as follows:

$$P(U=j)=\frac{\binom{M}{j}(1-\delta)^{j}\delta^{M-j}}{\sum_{l=\sigma}^{M}\binom{M}{l}(1-\delta)^{l}\delta^{M-l}} \tag{1}$$

for all $j\in\{0,\cdots,M\}$. Let V denote the number of copies in which no error occurs among the U copies (in which no error is detected when the receiving node sends a PACK message). Then, we have the conditional mass for V as

$$P(V=i\,|\,U=j)=\binom{j}{i}\left[\frac{1-\varepsilon}{1-\delta}\right]^{i}\left[\frac{\varepsilon-\delta}{1-\delta}\right]^{j-i} \tag{2}$$

for all $i\in\{0,\cdots,j\}$ and $j\in\{0,\cdots,M\}$. We define the probability of error remains to be the probability that a packet which was positively acknowledged by the receiving node is still being infected with errors. Such error remains are produced by the receiving node's wrong decision for a correct copy. Note that a wrong decision in the majority rule is incurred by the fact that the copies which are identically infected with errors form a majority. Let θ denote the probability of error remains. Note that the probability θ is lower than the probability that the number of copies in which no error occurs is smaller than the number of the remainder among the M copies. Thus, we have an upper bound of θ as follows:

$$\begin{aligned}\theta^{+} &\overset{\triangle}{=}\sum_{j=\sigma}^{M}\left[\sum_{i=0}^{\lceil \frac{j}{2}\rceil}P(V=i\,|\,U=j)P(U=j)\right]\\ &\quad\cdot I_{\{j \bmod 2=1\}}\\ &+\sum_{j=\sigma}^{M}\left[\sum_{i=0}^{\lceil \frac{j}{2}\rceil-1}P(V=i\,|\,U=j)P(U=j)\right.\\ &\quad\left.+\frac{1}{2}P(V=\lceil \tfrac{j}{2}\rceil\,|\,U=j)P(U=j)\right]\\ &\quad\cdot I_{\{j \bmod 2=0\}}.\end{aligned} \tag{3}$$

On the other hand, since the probability θ is higher than the probability that there is no copy in which no error occurs among the U copies (in which no error is detected when the receiving node sends a PACK message), we have the following lower bound on θ.

$$\theta^{-}\overset{\triangle}{=}\sum_{j=\sigma}^{M}P(V=0\,|\,U=j)P(U=j). \tag{4}$$

3.2 Packet Loss Probability

There are two causes invoking packet loss. One is the finiteness of the maximum number of retransmissions allowed for each packet and the other is the possibility of error remains in a positively acknowledged packet. Let π denote the probability that the receiving node sends a retransmission request after inspecting the received M copies of a packet for error. Note that according to the (M,σ) rule, a retransmission request is issued if the number of copies in which no error is detected is strictly less than the threshold value σ. Thus, we have

$$\pi=\sum_{j=0}^{\sigma-1}\binom{M}{j}(1-\delta)^{j}\delta^{M-j}. \tag{5}$$

Since only ν retransmissions are maximally permitted for each packet, the probability that a packet is declared to be lost is yielded to be $\pi^{\nu+1}$. (Remind that a packet is declared to be lost if errors are detected in more than $M-\sigma$ copies in the νth retransmission of the packet.) Thus, the packet loss probability, denoted by ψ is expressed as

$$\psi=\pi^{\nu+1}+(1-\pi^{\nu+1})\theta \tag{6}$$

where θ is the probability of error remains. Using the upper and lower bounds on the probability θ given in (3) and (4), we also have upper and lower bounds on the packet loss probability ψ as follows:

$$\phi^{+} \stackrel{\triangle}{=} \pi^{\nu+1}+(1-\pi^{\nu+1})\theta^{+} \qquad (7)$$
$$\phi^{-} \stackrel{\triangle}{=} \pi^{\nu+1}+(1-\pi^{\nu+1})\theta^{-}.$$

3.3 Packet Delay Time

In this section, we present analytical method to calculate the moments of packet delay time (at steady state) for stop-and-wait MC-ARQ as well as go-back-N MC-ARQ following the (M, σ) rule.

We assume that the packet arrivals at the transmitting node follow a Bernoulli batch arrival process, (i.e., at most a single batch of packets arrives in each slot and the batch arrival events occur mutually independently with an identical probability), where each batch is assumed to arrive at the end of a slot. Let γ denote the probability that a batch of packets arrives in a slot. We set the number of packets belonging to each batch to have a same distribution with a random variable B independently. The time unit is set to be the slot duration time, which is also set to be 1 without loss of generality. We define the round trip delay time $\omega \stackrel{\triangle}{=} \lfloor 2\xi \rfloor$ under the assumption that the transmission time of PACK (NACK) message is negligibly short.

Since the forward channel is assumed to be a BSC, each packet experiences an independent and identically distributed number of retransmissions. Let Q denote the number of retransmissions of a packet. Since the number of retransmissions is limited to ν, we have

$$P(Q=j) = (1-\pi)\pi^{j}$$
$$P(Q=\nu) = \pi^{\nu} \qquad (8)$$

for $j \in \{0, \cdots, \nu-1\}$, where π is the probability of retransmission request given in (5). Define the packet completion time of type A to be the time elapsed from the moment the first transmission of the packet starts until the ACK message for the last transmission of the packet arrives at the transmitting node. (Note that the packet completion time of type A is the time that the original packet sojourns at the top of the queue in the transmitting node.) We also define the packet completion time of type B to be time from the moment the first transmission of the packet starts until the last transmission of the packet is finished.

For $\Delta \in \{\mathrm{A}, \mathrm{B}\}$, let S^{Δ} denote the packet completion time of type Δ. Then,

$$S^{\mathrm{A}} = [M+\omega]Q+[M+\omega]$$
$$S^{\mathrm{B}} = [M+\omega]Q+M. \qquad (9)$$

Using the packet completion times given in (9), define batch completion times of two types, denoted by C^{A} and C^{B} as follows:

$$C^{\Delta} = \sum_{i=1}^{B} S_i^{\Delta} \qquad (10)$$

for $\Delta \in \{\mathrm{A}, \mathrm{B}\}$, where $S_1^{\Delta}, S_2^{\Delta}, \cdots$ are independent random variables governed by the same distribution as S^{Δ}.

Note that the batch completion times of each type are independent and identically distributed. Since the sequence of batch arrival times at the transmitting node is a Bernoulli point process with parameter γ, we can construct Geom/G/1 queueing systems of two types in which the batch arrival rate is γ and the batch service time has the same distribution with C^{A} and C^{B}, respectively. Define the batch waiting time to be the time elapsed from the moment the batch arrives until the service for the first packet of the batch starts. Let W_n^{Δ} denote the waiting time of the nth batch at the queueing system of type Δ. If $\gamma E(C^{\Delta}) < 1$, then there exists a random variable W^{Δ} such that $W_n^{\Delta} \xrightarrow{d} W^{\Delta}$ as $n \to \infty$ [5]. Let ϕ_W^{Δ} denote the generating function of the mass for W^{Δ} for $\Delta \in \{\mathrm{A}, \mathrm{B}\}$. Then, using the

Markov property of the remaining packet numbers (at the corresponding queueing system) embedded at departure points, we have [6]

$$\phi_W^{\Delta}(a)=\frac{[1-\gamma E(C^{\Delta})][1-a]}{[1-a]-\gamma[1-\phi_C^{\Delta}(a)]} \tag{11}$$

for $a\geq 0$, where ϕ_C^{Δ} is the generating function of the mass for C^{Δ}. We note that the service for a packet belonging to a batch is postponed until the service for the all previous packets belonging to the same batch is completed after the service for the first packet of the batch starts. Let W_{EX}^{Δ} denote such extra waiting time of a packet in the queueing system of type Δ at steady state and ϕ_{WEX}^{Δ} be the generating function of the mass for W_{EX}^{Δ}. Then, from renewal theory, we have [6]

$$\phi_{WEX}^{\Delta}(a)=\frac{\phi_B(\phi_S^{\Delta}(a))}{E(B)[1-\phi_S^{\Delta}(a)]} \tag{12}$$

where ϕ_B and ϕ_S^{Δ} are generating functions of the masses of B and S^{Δ}, respectively. Suppose that a PACK message is sent by the receiving node for a packet.

Let $\overline{Q}$ denote the number of retransmissions of the positively acknowledged packet until the PACK message arrives at the transmitting node. Then,

$$P(\overline{Q}=j)=\frac{(1-\gamma)\gamma^j}{1-\gamma^{\nu+1}} \tag{13}$$

for $j\in\{0,\cdots,\nu\}$. Let $\overline{S}$ denote the type A completion time of such positively acknowledged packet. Then, we have

$$\overline{S}=[M+\omega]\overline{Q}+[M+\omega]. \tag{14}$$

Define the delay time of a positively acknowledged packet to be the time elapsed from the moment the packet (the batch of the packet) arrives until the PACK message arrives at the transmitting node. For stop-and-wait MC-ARQ and go-back-N MC-ARQ following the (M,σ) rule, let $\overline{D}_{SAW}$ and $\overline{D}_{GBN}$ be the delay time experienced by a positively acknowledged packet at steady state, respectively. Then, the packet delay times are represented as [6][7]

$$\begin{aligned}\overline{D}_{SAW} &= W^{\mathrm{A}}+W_{EX}^{\mathrm{A}}+\overline{S}\\ \overline{D}_{GBN} &= W^{\mathrm{B}}+W_{EX}^{\mathrm{B}}+\overline{S}.\end{aligned} \tag{15}$$

Let ϕ_D^{SAW} and ϕ_D^{GBN} denote the generating functions of the masses for $\overline{D}_{SAW}$ and $\overline{D}_{GBN}$, respectively. Then, we have

$$\begin{aligned}\phi_D^{SAW}(a) &= \phi_W^{\mathrm{A}}(a)\phi_{WEX}^{\mathrm{A}}(a)\phi_{\overline{S}}(a)\\ \phi_D^{GBN}(a) &= \phi_W^{\mathrm{B}}(a)\phi_{WEX}^{\mathrm{B}}(a)\phi_{\overline{S}}(a).\end{aligned} \tag{16}$$

Differentiating both sides of (16), we obtain the moments of $\overline{D}_{SAW}$ and $\overline{D}_{GBN}$.

3.4 Maximum Throughput

Let η_{SAW} and η_{GBN} be the maximum throughput in stop-and-wait MC-ARQ and go-back-N MC-ARQ following the (M,σ) rule, respectively. In stop-and-wait MC-ARQ, only one packet can be sent to the receiving node during the packet completion time S^{A} given in (9). Similarly, only one packet can be sent to the receiving node during the packet completion time S^{B} in go-back-N MC-ARQ. Considering the packet loss due to finite retransmissions and error remains, we obtain the maximum throughput as follows:

$$\begin{aligned}\eta_{SAW} &= \frac{1-\psi}{E(S^{\mathrm{A}})}\\ \eta_{GBN} &= \frac{1-\psi}{E(S^{\mathrm{B}})}\end{aligned} \tag{17}$$

where ψ is the packet loss probability in (6). Using the upper and lower bounds on the packet loss probability in (7), we have upper and lower bounds on maximum throughput as follows:

$$\begin{aligned}\frac{1-\psi^+}{E(S^{\mathrm{A}})} &\leq \eta_{SAW} \leq \frac{1-\psi^-}{E(S^{\mathrm{A}})}\\ \frac{1-\psi^+}{E(S^{\mathrm{B}})} &\leq \eta_{GBN} \leq \frac{1-\psi^-}{E(S^{\mathrm{B}})}.\end{aligned} \tag{18}$$

Ⅳ. Numerical Examples

In this section, using the analytical method developed in section 3, we investigate the effect of the parameters of the (M,σ) rule, channel's bit error rate and traffic load at the transmitting node on the probability of error remains, packet loss probability, mean packet delay time, and maximum throughput. In numerical examples, the probability δ, (i.e., the probability that errors occur in a copy and such errors are not detected) must be specified. For Hamming codes, the minimum distance and weight distribution are already reported and the probability δ can be analytically calculated [8]. By this reason, we use a Hamming code (especially, $(1023, 1013)$ Hamming code) in the numerical examples of this section. Also, we set the data rate and the propagation delay time so that the round trip delay time is equal to the slot duration time. The maximum number of retransmissions is limited to 5 times and the number of copies made per packet M is fixed to 5. The parameter values used in the following figures are summarized in table 1.

Table 1 Parameter values used in section 4
표 1. 4 장에 사용된 파라미터 값

parameter		
packet length	N	1023
the num. of copies per	M	5
the max. num. of	ν	5 times
round trip delay time	ω	1 slot

In figure 1, we show the probability of error remains with respect to bit error rate. As expected, the probability of error remains is significantly reduced by adopting the (M,σ) rule (compared with the conventional ARQ scheme of sending single copy per packet, denoted as SC-ARQ). We also observe that the probability of error remains decreases as the threshold value σ increases.

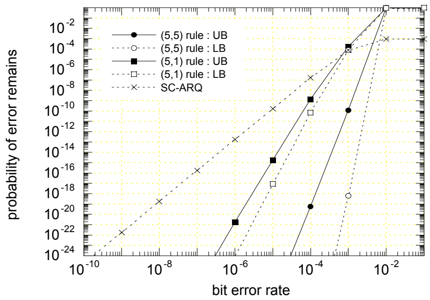

Fig. 1 Probability of error remains with respect to bit error rate
그림 1. 비트 오류율에 따른 오류 잔류확률

In figure 2, we show the packet loss probability with respect to bit error rate. In this figure, we confirm that compared with the SC-ARQ, the MC-ARQ following the (M,σ) rule can reduce packet loss probability as well as probability of error remains with setting a proper threshold value σ.

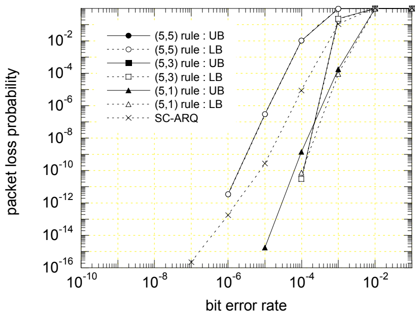

Fig. 2 Packet loss probability with respect to bit error rate
그림 2. 비트 오류율에 따른 패킷 상실확률

In figure 3, we show the maximum throughput with respect to bit error rate. In this figure, we observe that the maximum throughput decreases as σ increases. Such observation indicates that the packet loss due to the finite retransmissions dominantly affects the maximum throughput rather than the packet loss induced by error remains.

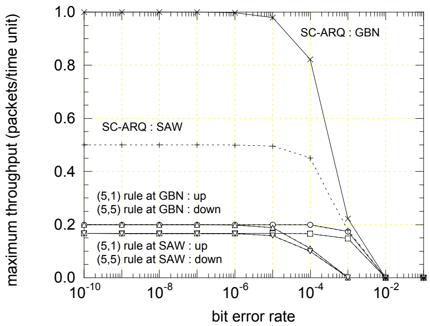

Fig. 3 Maximum throughput with respect to bit error rate
그림 3. 비트 오류율에 따른 최대 throughput

In figure 4, we show the mean packet delay time with respect to traffic load. In this figure, the bit error rate is set to 0.001. We observe that the mean packet delay time increases as σ increases, which results from the fact that the number of retransmissions increases as σ increases. Also, go-back-N MC-ARQ exhibits better mean delay performance than stop-and-wait MC-ARQ in relatively low bit error rate.

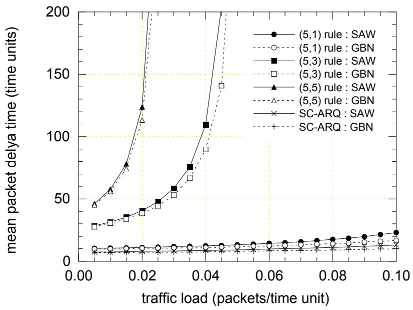

Fig. 4 Mean packet delay time with respect to bit error rate
그림 4. 비트 오류율에 따른 평균 패킷 지연 시간

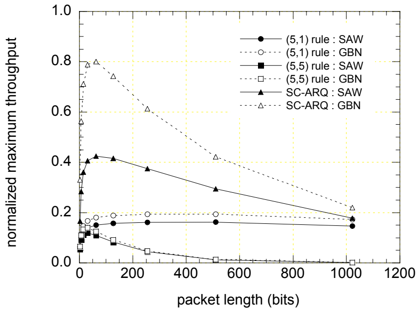

Fig. 5 Normalized maximum throughput with respect to packet length
그림 5. 패킷 길이에 따른 정규화된 최대 throughput

In figure 5, we show the normalized throughput with respect to the packet length. In this figure, the bit error rate is set to 0.001 and Hamming codes are used to encode payload. We observe that the normalized maximum throughput in SC-ARQ is generally higher than the one in MC-ARQ, We also notice that there exists an optimal length of packet which minimizes the normalized maximum throughput.

V. Conclusions

In this paper, we considered stop-and-wait and go-back-N multicopy transmission ARQ schemes and proposed a rule of requesting packet retransmission and deciding a correct copy, identified as (M, σ) rule. The (M, σ) rule is able to reduce the probability of error remains by use of time diversity combining, while the throughput and delay performance may be degraded as side-effects of the rule. Thus, we developed analytical methods to evaluate the performance trade-off of the (M, σ) rule and investigated the effect of bit error rate and traffic load on the performance of error remains, packet loss, packet delay, and throughput. In numerical examples, we observed that we can reduce the probability of error remains as well as packet loss probability by properly setting the value of σ, and confirmed the adaptability of the (M, σ) rule to meet various QoS requirements.

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